New paradigms for determining structural design loads for blast

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Probabilistic explosion analysis, outlined in NORSOK Standard Z-013 as well as ISO 19901-3, is commonly used in industry to determine the design explosion loads at a given probability of acceptance. The probabilistic approach involves the simulation of a large dataset of individual scenarios covering each stage in the sequence of events leading up to an explosion – predicting the background ventilation behaviour during normal operations, the dispersion behaviour following a loss of containment, and the explosion dynamics following the delayed ignition of accumulated hydrocarbons. In our experience, it is usually necessary to reduce the huge amount of predictive data generated into just a few exceedance curves describing the predicted explosion risk at selected targets of interest.

The use of simulation data management (SDM) tools and implementation of new, 'smarter' approaches can lead to better, safer, and more cost-effective design. Specifically, it enables 3D risk assessment information to be automatically compiled where, for example, the spatial variation of an explosion load can be presented across a structural target of interest, rather than just a single worst-case load that is read from a traditional exceedance curve. Further, one can automatically map explosion loads determined using computational fluid dynamics (CFD) simulations on to a finite element analysis (FEA) model so that the associated structural response can be simulated by coupling explosion CFD and non-linear FEA (NLFEA) analyses.

This work examines two approaches for mapping CFD explosion loads on to an FEA model: (a) constructing a 10^{-4}/year pseudo-event by combining simulated events, and (b) one-to-one coupling between explosion CFD and NLFEA (probabilistic structural response). A case study focusing on explosion loads on a blast wall on an offshore oil and gas facility is presented. For this case study, it is found that there is reasonable agreement between the pseudo-event and probabilistic structural response approaches. However, it remains unclear whether this is generally the case – the blast wall considered is a fairly stiff design, and it is thought that for less stiff structures this agreement may diminish. It is recommended that further work is undertaken to investigate this.

Nonetheless, the traditional approach with a worst-case load uniformly applied across the structure is clearly overly conservative when compared to the probabilistic structural response and pseudo-event approaches.

Introduction and motivation

Since the conception of the NORSOK Standard Z-013 (NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK Standard Z-013 Edition 3 (October 2010), Available from: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standard-categories/z-risk-analyses/z-0132/.) in the late 1990s, the industry has steadily moved towards a probabilistic approach for modelling explosion risk in line with the recommended procedure outlined in Annex F of that standard. The procedure describes how a quantitative explosion risk assessment should preferably be carried out with the use of computational fluid dynamics (CFD) tools for ventilation, dispersion and explosion calculations. The purpose of the procedure is to standardise the analyses so that the risk of explosions can be compared between different areas, installations and concepts, even if the analyses are performed in different circumstances and by different personnel.

The probabilistic approach based on CFD, which is now also recommended in international ISO standards (ISO 19901-3, 2010. Petroleum and natural gas industries − Specific requirements for offshore structures - Part 3: Topsides structure, Available from: https://www.iso.org/standard/43812.html), involves the simulation of a large dataset of individual scenarios covering each stage in the sequence of events leading up to an explosion in order to determine explosion loads, such as overpressures and drag loads. This exercise, combined with an understanding the frequencies of occurrence at each stage, allows exceedance curves for the explosion load at the targets of interest to be constructed. Exceedance curves show the predicted frequency for explosion loading at a target of interest. For a specified allowable frequency, the design load is read from the curve and can be used as the basis of the structural design. An example is shown in Figure 1.

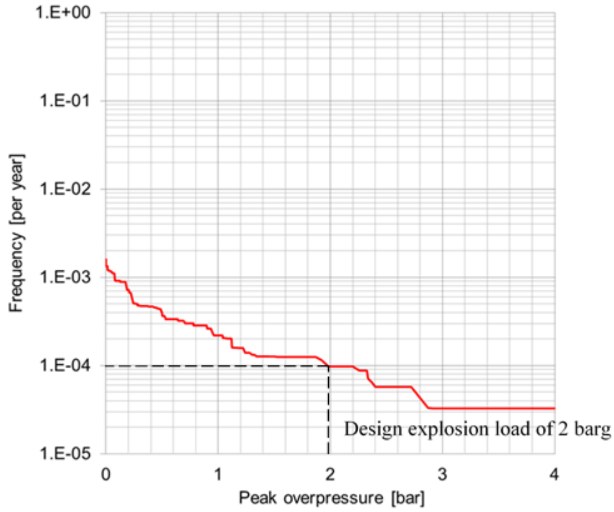


Figure 1 A typical exceedance curve for the explosion load on a target of interest, such as a blast wall, determined using probabilistic explosion analysis with the CFD approach (NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK Standard Z-013 Edition 3 (October 2010), Available from: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standard-categories/z-risk-analyses/z-0132/.**)**

The probabilistic explosion analysis is often a substantial undertaking, and for this reason, it is often performed by a CFD team that is entirely separate from the structural design team that will use the outputs from the modelling. In our experience, the interface between the two parties is often primitive. Consequently, it is usually necessary to reduce the huge amount of predictive data generated as part of the probabilistic assessment into just a few exceedance curves describing the predicted frequency corresponding to the explosion load at selected targets of interest, so that the information can be easily transferred to the structural team. However, with a little thought and imagination, the predictive data accumulated can be presented in ways that provide improved insight, which can lead to a better as well as safer design.

The key to this is simulation data management, or SDM (NAFEMS WT02, What is simulation data management?, Available from: https://www.nafems.org/downloads/sdmwg/nafems_wt02_-_what_is_simulation_data_management.pdf). Indeed, whenever there are a large number of individual simulations, we argue that SDM should be considered to keep track of the individual simulations and automate the workflow. Effective SDM tools can offer the following benefits:

- Provision of a robust, consistent method for the implementation of the NORSOK Standard Z-013, provided the underlying implementation is openly documented.
- Sharing of the predictive data with the design team and democratisation of the probabilistic approach, allowing the sensitivity of the exceedance data to many of the probabilistic assumptions to be investigated on-the-fly, in the company of the wider design team.

The SDM tools also allow the following benefits to be realised:

- Automatic compilation of 3D risk assessment information where, for example, the spatial variation of an explosion load can be presented across larger structural targets of interest, rather than just a single worst-case load that is read from a traditional exceedance curve.
- Automatic mapping of CFD explosion loads onto non-linear structural finite element analysis (FEA) models using one-to-one coupling between CFD and non-linear FEA (NLFEA) codes, thus extending the probabilistic method to include structural response.

Democratisation of the probabilistic approach

The application of SDM to a probabilistic explosion workflow essentially integrates the three stages of analysis (ventilation/dispersion/explosion). Using SDM, the relevant predictive data can be easily extracted from the underlying CFD simulation files, stored efficiently in text readable files, and packaged with lightweight tools that can be shared with the design team so that the whole team can better understand the probabilistic process and the implication of (some of) the assumptions upon the compiled exceedance data.

The packaged tool/data can be easily shared with the design team, thus democratising the approach. This can improve the interaction between the structural engineer and explosion analyst, which should lead to better, safer design.

We have developed the EXCGEN (exceedance curve generator) software for undertaking such probabilistic explosion/fire assessments. EXCGEN automates the substantial number of individual CFD simulations required for the underlying dataset of cases required for a probabilistic analysis, to ensure that they're set-up in a rigorous and consistent manner, and automates the construction of the exceedance curves for all targets of interest. There are similar developments by other consultancies and software providers, and it is hoped that these too will allow the easy sharing of data.

More importantly, this also allows sensitivity of the explosion loads to (some of) the probabilistic assumptions to be investigated with the design team on the fly, including for example, the ignition methodology, the underlying wind conditions, the flammable volume methodology and the release frequencies from the QRA.

Ignition probability is a key input for the determination of the explosion load. As an example, Figure 2 presents the exceedance curves on a certain target of interest on an oil and gas facility using six different ignition methodologies A-F based on the UKOOA model (Energy Institute, 2006, IP Research Report: Ignition probability review, model development and look-up correlations, Available from: http://publishing.energyinst.org/__data/assets/file/0004/25762/Pages-from-IP-Research-Report-Ignition-probability-review,-model-developmement-and-look-up-correlations-Jan-2006.pdf). It is apparent that the choice of the ignition methodology can have a significant impact, as the 10^{-4}/year explosion load, for example, can increase from 2 barg to over 4.5 barg.

In our experience, this level of interaction within the team is not typical (at least, not so interactively), but exploring sensitivities on the fly provides an excellent opportunity to discuss some of the uncertainties associated within the probabilistic approach with the design team, which can lead to much improved understanding for all parties.

3D risk assessment

Another key issue to consider is that the explosion loads, particularly for large targets such as blast walls, may vary spatially so providing a single value for the design load may be overly conservative. For example, the curve presented earlier in Figure 1 represents the exceedance curve for the explosion load for a blast wall on an FPSO. For a permissible frequency of occurrence of 10^{-4} /year, the corresponding design explosion load is 2 barg. Traditionally, this would be applied uniformly across the blast wall and the structural response determined accordingly, as shown in Figure 3.

Ignition methodology	Probability of ignition	Probability of explosion given ignition	Time dependence
A	UKOOA 25	Fixed at 20%	UKOOA
B	UKOOA 25	Cox, Lees and Ang	UKOOA
C	UKOOA 25	Ignored	UKOOA
D	UKOOA 25	Fixed at 20%	Ignored
E	UKOOA 25	Cox, Lees and Ang	Ignored
F	UKOOA 25	Ignored	Ignored

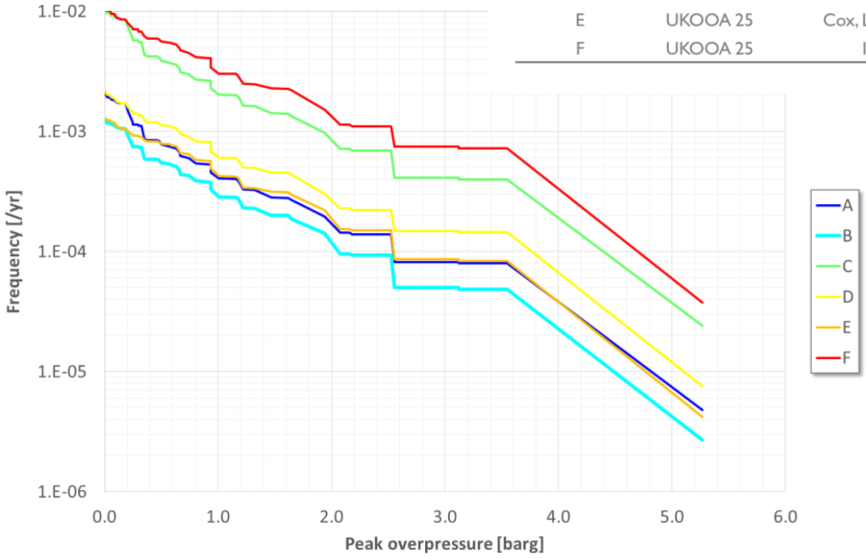


Figure 2 Sensitivity of exceedance curves for peak overpressure to six different ignition methodologies based on the UKOOA ignition model (summarised in table on the top)

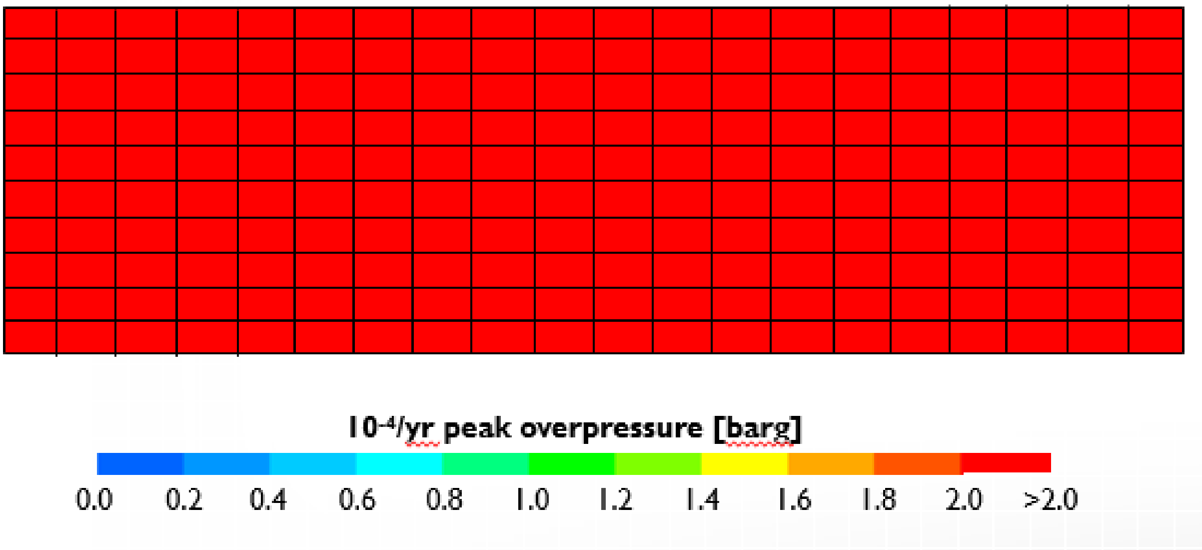


Figure 3 **The traditional approach for explosion load assessment where the 10^{-4} explosion load (2 barg in this case) is applied uniformly across the blast wall.**

However, large objects are typically represented by a discretised array of monitor panels within the CFD model. Using SDM methods, it is relatively straight forward to automatically compile individual exceedance curves for each panel in the array, read off the explosion load corresponding to the allowable frequency of interest, and plot this information spatially to investigate how the explosion load corresponding to that frequency may vary across the target.

This is shown for the blast wall under consideration in Figure 4 and, from this figure, it is immediately obvious that the 2 barg load derived from the exceedance curve is very localised – it is confined to the bottom right corner of the blast wall, which in this example was adjacent to a heavily congested compression module operating at high pressure. It is noted that the overpressures on the left side of the blast wall, which were adjacent to a separation module operating at lower pressure, are significantly lower, and this spatial variation can have a significant impact upon the structural response of the blast wall under DAL loading. The additional insight from considering this spatial variation, enabled using SDM, can help the structural engineers to design a more effective blast wall.

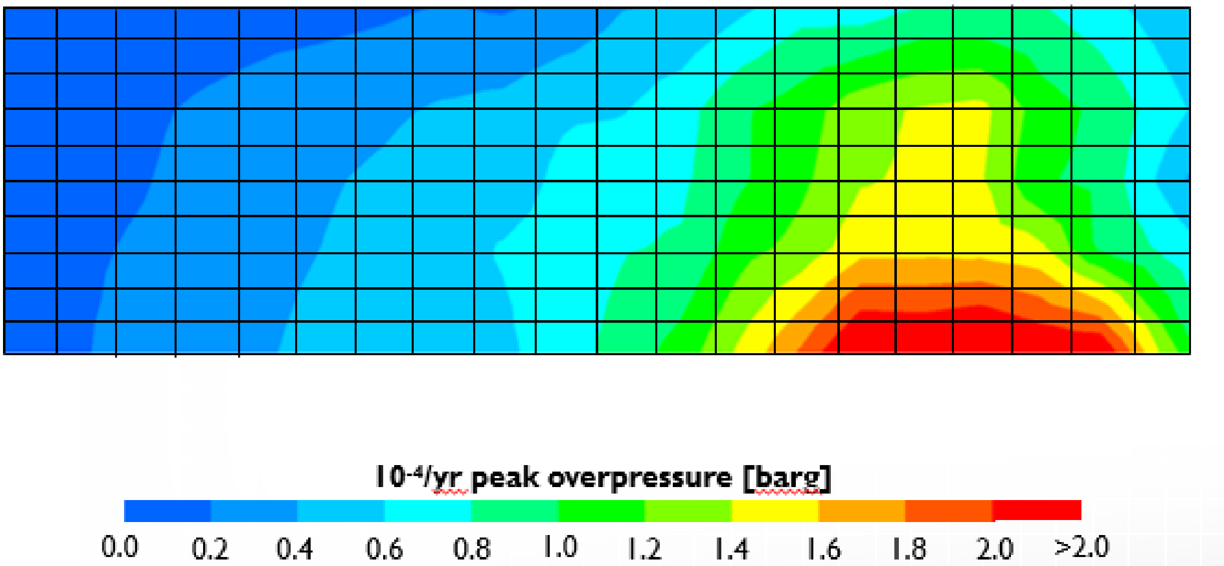


Figure 4 **The spatial variation of the design explosion load varies significantly across the blast wall, which implies that the traditional approach of applying constant design explosion load is too conservative**

Probabilistic structural response

When it comes to the structural design activities, it is typical to identify and/or construct representative blast events that can be used as the basis of the design. Rather than trying to identify representative explosion events from those within the simulated dataset, or constructing a representative pseudo-event by somehow combining multiple simulated events, another method is to directly simulate the response of the structure for each simulated explosion using non-linear finite element analysis (NLFEA). This is enabled through one-to-one coupling between the explosion CFD and structural FEA codes as part of an effective SDM tool – this is option B2 in Annex F of the NORSOK Standard Z-013, as shown in NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK Standard Z-013 Edition 3 (October 2010), Available from: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standard-categories/z-risk-analyses/z-0132/.).

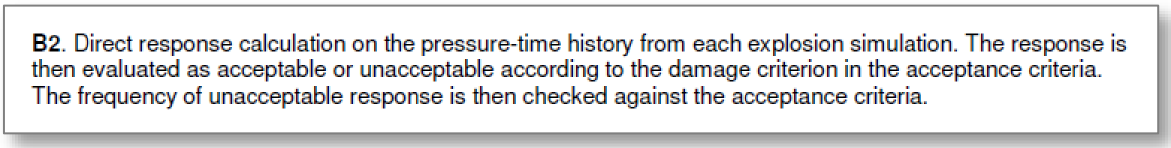

B2. Direct response calculation on the pressure-time history from each explosion simulation. The response is then evaluated as acceptable or unacceptable according to the damage criterion in the acceptance criteria. The frequency of unacceptable response is then checked against the acceptance criteria.

Figure 5 Direct NLFEA simulation of the structural response for each simulated explosion, enabled through one-to-one coupling between the explosion CFD and FEA codes, is described in the NORSOK Standard Z-013 (NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK Standard Z-013 Edition 3 (October 2010), Available from: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standard-categories/z-risk-analyses/z-0132/.**)**

This direct one-to-one coupling approach effectively extends the realm of the probabilistic approach to include structural response. Other researchers have considered similar approaches in the past (e.g. Frazer, R., Sari, A. and Nordstrom, M., 2013, Advances in structural design against fires and explosions, FABIG TM 75.; Salaun, N., Hanssen, A.G. and Nilsen, P.E., 2016, Risk-based structural response against explosion blast loads: systematic one-to-one CFD (FLACS)/ NLFEA (Impetus AFEA solver) coupling to derive quantified response exceedance, *Chem. Eng. Trans.* 48: 55-60.; Kang, K-Y., Choi, K-H., Choi, J.W., Ryu, Y.H. and Lee, J-M., 2017, Explosion induced dynamic responses of blast wall on FPSO topside: Blast loading application methods, Intl J Naval Arch Ocean Eng, 9(2): 135-148.).

The direct one-to-one coupling approach is attractive because it is a fundamental approach – it does not introduce any new assumptions.

This approach is demonstrated for the FPSO blast wall considered earlier. The structure of the blast wall considered is presented in Figure 6. The blast wall consists of structural columns to provide localised stiffness.

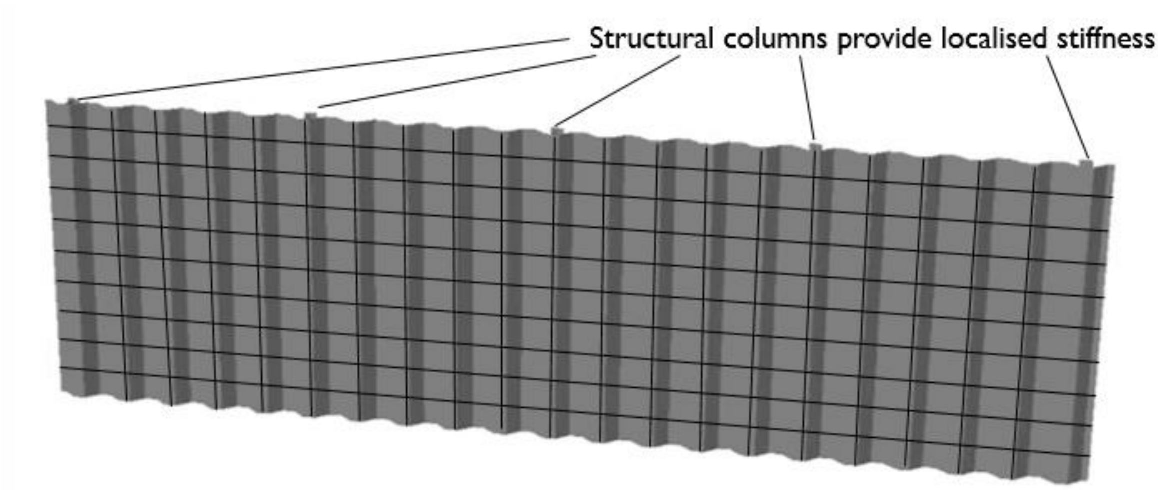
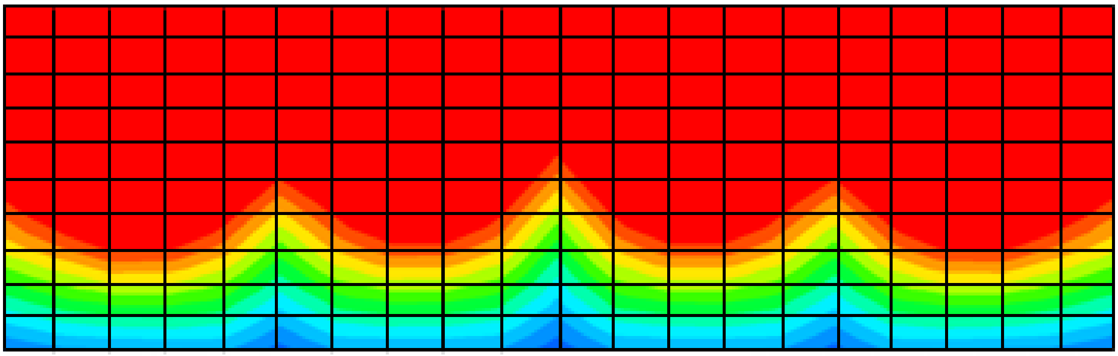


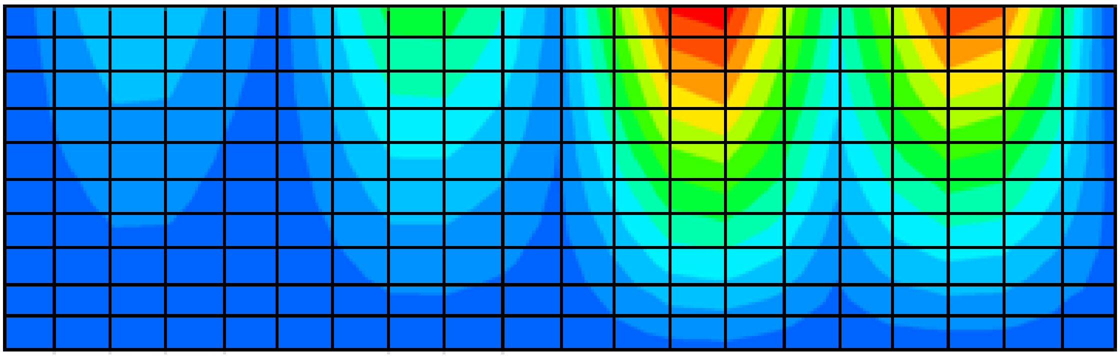
Figure 6 Structure of the blast wall used during the current study

The predicted blast histories from CFD are mapped at each panel for each explosion event, and individual exceedance curves for deflection are compiled from the NLFEA for each panel. The 10^{-4}/year deflection is then determined for each panel and plotted spatially across the blast wall, as shown in the lower part of Figure 7 – this is termed the probabilistic structural response approach and it is compared to the traditional approach, where the 10^{-4}/year overpressure (2 barg) from the exceedance curve is applied uniformly across the blast wall, as shown in the upper part of Figure 7. Clearly, the traditional approach is overly conservative when compared to the probabilistic structural response approach.

In the past, the probabilistic structural response approach may have been prohibitive in terms of computational effort, since the one-to-one coupling requires many NLFEA simulations to be undertaken – nominally one for each explosion event simulated. However, it is our assertion that with effective SDM tools and improving computing facilities, this approach is now feasible and could become more widespread. In our experience, the computational effort required for the NLFEA of specific structures can be comfortably undertaken alongside the rest of the probabilistic assessment (it is often the dispersion phase of the assessment which is the bottleneck). Further, not all explosion events necessarily need to be simulated using NLFEA – by starting with the larger events and working towards smaller events, a point is reached where the frequency-based measures of interest (for example, damage or deflection) stop changing.



Traditional approach



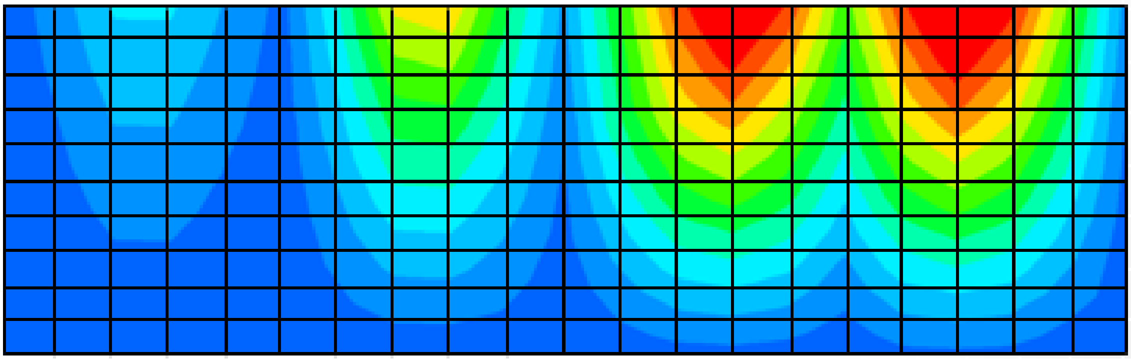
Probabilistic structural response through one-to-one coupling

Figure 7 Comparison of contours of 10^{-4}/year deflection, where blue is lowest and red is highest – (top plot) using the traditional approach, uniformly applying the 10^{-4}/year overpressure (2 barg) from the exceedance curve; (bottom plot) using a probabilistic structural response approach, enabled through one-to-one coupling between the explosion CFD and FEA codes.

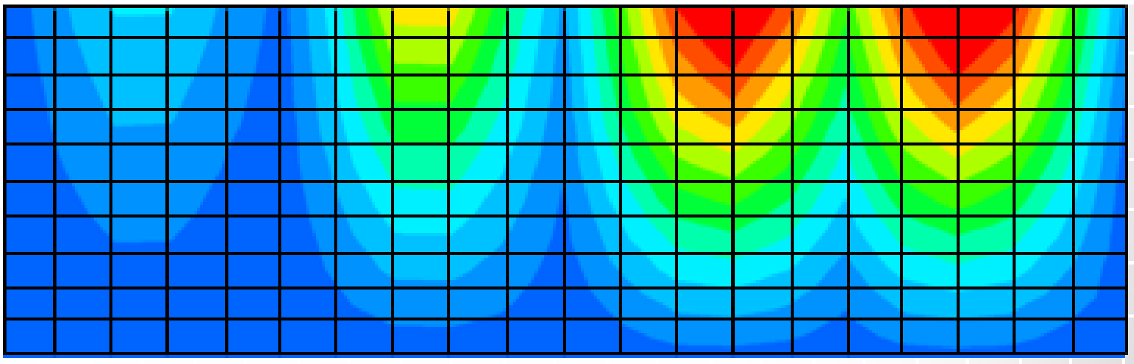
Representative 10^{-4} /year explosion pseudo-event

Whilst it may now be feasible, the probabilistic structural response approach with one-to-one coupling between CFD and NLFEA does represent an increase in computational effort and, to address this, the possibility of constructing a representative 10^{-4}/year pseudo-event from the simulated explosion events is also considered – which may then reduce the required NLFEA efforts to a single simulation for the pseudo-event for the purpose of determining the structural response of the blast wall. In the current paper, the pseudo-event is carefully constructed and comprises contributions from many individual explosion events. The spatial variation of peak over-pressure is constructed using the methodology described for the plot in Figure 4, and the duration of the blast (both the positive blast phase and negative blast phase) is derived by considering the predicted trends for the underlying simulated explosion data set, which allows a (triangulated) 10^{-4}/year pseudo-blast to be imposed at each panel across the blast wall.

Two variations of pseudo-event are considered – with the blast impinging everywhere simultaneously, and with a time delay to mimic the progress of the blast across the wall based upon the local speed of sound. The 10^{-4}/year deflection contours are presented for both pseudo-event approaches (with and without time delay) in Figure 8.



Without time delay – blast impinging everywhere simultaneously



With time delay – based upon the local speed of sound

Figure 8 Comparison of contours of 10^{-4}/year deflection, where blue is lowest and red is highest – (top plot) using the 10^{-4}/year pseudo-event without time delay; (bottom plot) using the 10^{-4}/year pseudo-event with time delay.

For the case study considered, there is in fact reasonable agreement between both of the pseudo-events and probabilistic structural response approaches. However, we need to consider a much wider range of examples to determine whether this is generally the case, so this remains an open question. However, it remains unclear whether this is generally the case – the blast wall considered is a fairly stiff design, and it is thought that for less stiff structures this agreement may diminish. It is recommended that further work is undertaken to investigate this.

It is, however, stressed that the one-to-one coupling approach does not require the definition of a 10^{-4}/year pseudo-event and is, therefore, free from any new assumptions that may need to be justified. From this perspective, it is the preferred approach.

Consistency across the industry

Potential inconsistency and benchmarking exercises

It is of concern to the industry that if two different organisations, or even two different individuals within the same organisation, are asked to undertake a probabilistic assessment, it is highly likely that the exceedance data constructed by the two parties will be different. There are many open questions within the probabilistic methodology and yet there is nothing akin to a worked example on how to undertake an assessment. Such user variation and inconsistencies in the approach and detailed assumptions are bad for our industry. Whilst there might be high-level agreement within the industry regarding the general probabilistic approach, the devil is very often in the detail, so without industry guidance on the detailed approach there is inevitably scope for inconsistency to become manifested.

We propose that better practical guidance is required for the industry, which should document the probabilistic methodology in detail, with practical worked examples so that there are actual numbers to compare against. Perhaps a blind benchmarking exercise should be undertaken to investigate whether there is indeed variation across the industry and, if so, to provide an indicative quantification of the degree of variation.

A similar benchmarking exercise was organized several years ago by Statoil for Norwegian safety consultants (Holen, J., 2001. Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants, ERA Conference, London, UK.). Five different organizations were asked to perform the same probabilistic explosion study for the Huldra Platform, and an example of the results is shown in Holen, J., 2001. Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants, ERA Conference, London, UK.

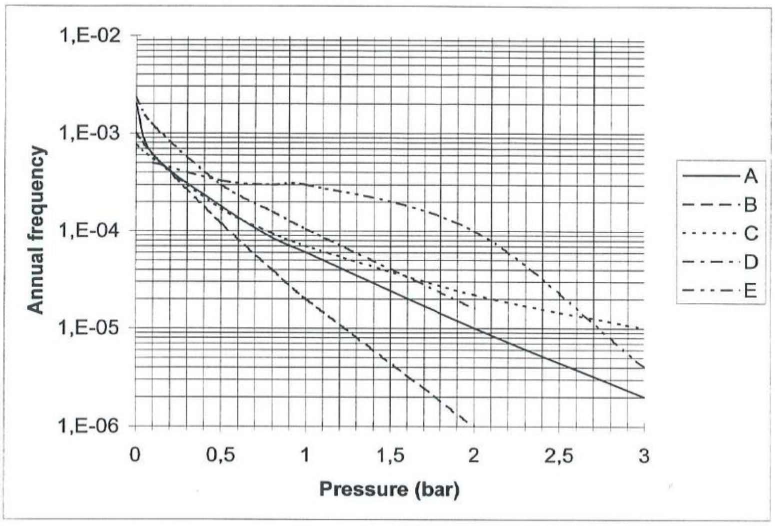


Figure 9 Example of results from the probabilistic explosion analysis benchmark (Holen, J., 2001. Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants, ERA Conference, London, UK.**). 4 organisations (A-D) predicted 10^{-4}/year explosion load between 0.5-1.1 barg while group E predicted much higher values of about 2 barg (using steady state dispersion).**

It was clear that there were differences in approach between the parties, and the work allowed some of these differences to be better understood, which potentially allowed the consistency between the parties to be improved. Without this kind of benchmarking exercise, it is not possible to identify and quantify the effect of any differences in approach that may exist, so any inconsistencies may simply propagate.

NAFEMS oil and gas focus group

A relevant example of industry coming together to address concerns regarding consistency is the NAFEMS oil and gas focus group which was established in 2016. NAFEMS is the international association for the engineering modelling, analysis and simulation community and focusses on the practical application of numerical engineering simulation techniques such as finite element analysis, computational fluid dynamics, and multibody simulation. The oil and gas focus group was established to:

- review existing guidance in the oil and gas sector relating to the use of simulation, and identify where there are gaps within the existing guidance
- develop a coordinated series of How To guides to provide practical guidance for simulation users in the oil and gas sector.

SDM as a vehicle to improve consistency

One of the major benefits of an automated SDM approach is that it can provide a robust, consistent method for the implementation of the probabilistic methodology. Abercus uses EXCGEN, many other consultants have developed their own in-house tools that have similar functionality. The software providers Gexcon and ComputIT are developing RISK and RBM respectively. The recent emergence of these SDM tools is generally welcomed, provided the methodology implemented within each tool is openly documented so that the probabilistic approach can be consistent among these tools.

Final words

Effective use of SDM tools can allow data to be shared with the design team, thus democratising the approach. SDM can enable:

- The sensitivity of the exceedance data to many of the probabilistic assumptions to be explored on-the-fly, in the company of the wider design team
- 3D risk assessment information to be presented, where the spatial variation of an explosion load is presented across large structures, which can provide additional insight for better, more effective structural design

- One-to-one coupling between explosion CFD and NLFEA, extending the probabilistic methodology to cover structural response.

As new methods are enabled though software tools, there may be a need for updated guidance and benchmarking to minimise inconsistency across our industry. We believe that there is an urgent need for new practical guidance describing the probabilistic methodology in detail in order to minimise any inconsistency that may exist across our industry – perhaps from organisations including NAFEMS, IChemE and FABIG.

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2 Frazer, R., Sari, A. and Nordstrom, M., 2013, Advances in structural design against fires and explosions, FABIG TM 75.

3 Holen, J., 2001. Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants, ERA Conference, London, UK.

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6 NAFEMS WT02, What is simulation data management?, Available from: https://www.nafems.org/downloads/sdmwg/nafems_wt02_-_what_is_simulation_data_management.pdf)

7 NORSOK, 2010, Risk and emergency preparedness assessment, NORSOK Standard Z-013 Edition 3 (October 2010), Available from: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standard-categories/z-risk-analyses/z-0132/.

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